

## Water Resources Research

### COMMENTARY

10.1002/2016WR020175

#### Key Points:

- ET science and applications have significantly advanced across a wide array of fields over the past several decades
- Critical outstanding ET-based research and applied science questions from local to global scales remain due to deficiencies in our observational capabilities
- National and international research priorities should include ET-focused satellite observational investments and programs

#### Correspondence to:

J. B. Fisher,  
jbfisher@jpl.nasa.gov

#### Citation:

Fisher, J. B., et al. (2017), The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources, *Water Resour. Res.*, 53, 2618–2626, doi:10.1002/2016WR020175.

Received 23 NOV 2016

Accepted 11 FEB 2017

Accepted article online 11 MAR 2017

Published online 10 APR 2017

## The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources

Joshua B. Fisher<sup>1</sup> , Forrest Melton<sup>2</sup>, Elizabeth Middleton<sup>3</sup>, Christopher Hain<sup>4,5</sup>, Martha Anderson<sup>6</sup>, Richard Allen<sup>7</sup>, Matthew F. McCabe<sup>8</sup> , Simon Hook<sup>1</sup>, Dennis Baldocchi<sup>9</sup> , Philip A. Townsend<sup>10</sup>, Ayse Kilic<sup>11</sup>, Kevin Tu<sup>12</sup> , Diego D. Miralles<sup>13</sup> , Johan Perret<sup>14</sup>, Jean-Pierre Lagouarde<sup>15</sup>, Duane Waliser<sup>1</sup> , Adam J. Purdy<sup>1</sup> , Andrew French<sup>16</sup> , David Schimel<sup>1</sup>, James S. Famiglietti<sup>1</sup>, Graeme Stephens<sup>1</sup> , and Eric F. Wood<sup>17</sup> 

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, <sup>2</sup>NASA Ames Research Center Cooperative for Research in Earth Science in Technology, Moffett Field, California, USA, <sup>3</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, <sup>4</sup>NASA Marshall Space Flight Center, Huntsville, Alabama, USA, <sup>5</sup>NOAA National Environmental Satellite, Data, and Information Service, College Park, Maryland, USA, <sup>6</sup>U.S. Department of Agriculture, Beltsville, Maryland, USA, <sup>7</sup>University of Idaho, Kimberly, Idaho, USA, <sup>8</sup>King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, <sup>9</sup>University of California, Berkeley, California, USA, <sup>10</sup>University of Wisconsin, Madison, Wisconsin, USA, <sup>11</sup>University of Nebraska-Lincoln, Lincoln, Nebraska, USA, <sup>12</sup>DuPont Pioneer, Johnston, Iowa, USA, <sup>13</sup>Ghent University, Ghent, Belgium, <sup>14</sup>EARTH University, San, José, Costa Rica, <sup>15</sup>INRA, ISPA UMR 1391, Villenage D'Ornon, France, <sup>16</sup>U.S. Department of Agriculture, Maricopa, Arizona, USA, <sup>17</sup>Princeton University, Princeton, New Jersey, USA

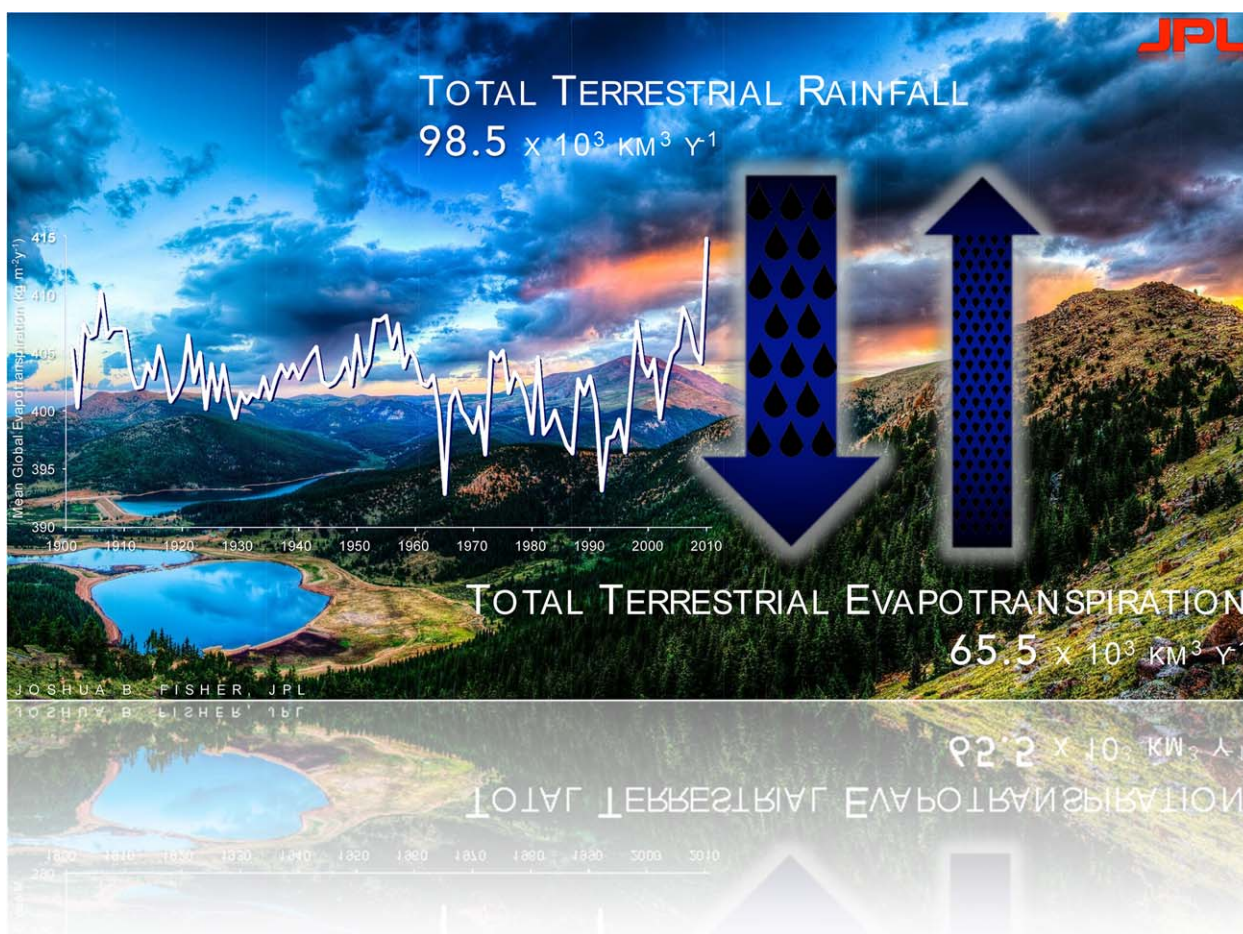
**Abstract** The fate of the terrestrial biosphere is highly uncertain given recent and projected changes in climate. This is especially acute for impacts associated with changes in drought frequency and intensity on the distribution and timing of water availability. The development of effective adaptation strategies for these emerging threats to food and water security are compromised by limitations in our understanding of how natural and managed ecosystems are responding to changing hydrological and climatological regimes. This information gap is exacerbated by insufficient monitoring capabilities from local to global scales. Here, we describe how evapotranspiration (ET) represents the key variable in linking ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources, and highlight both the outstanding science and applications questions and the actions, especially from a space-based perspective, necessary to advance them.

### 1. Introduction

The response of the terrestrial biosphere to changes in climate remains one of the largest sources of uncertainty in climate projections [Friedlingstein et al., 2014]. Tightly coupled to the water cycle, ecosystems can act as either carbon sinks (photosynthesis, primary production) or carbon sources (respiration, decomposition, mortality, combustion), and provide climate feedbacks through latent heat fluxes, albedo, and water cycling. However, the water cycle is rapidly changing, resulting in greater variance and more extremes [Ziegler et al., 2003; Syed et al., 2010]. For example, the worst drought in its recorded history struck the Amazon basin in 2005, reversing this long-term carbon sink into a carbon source [Phillips et al., 2009]. In 2010, an even stronger drought hit the Amazon basin, which had not fully recovered from the impacts of the earlier event, and 2015 saw yet another recurrence [Lewis et al., 2011; Saatchi et al., 2013; Jiménez-Muñoz et al., 2016]. The United States Midwest also experienced its worst drought in decades in 2011, followed by an even stronger one in 2012, which impacted 80% of US agriculture; in parallel, a multiyear drought from 2012 to 2015 along the West coast significantly impacted food production for the entire country [Long et al., 2013; Mallya et al., 2013; AghaKouchak et al., 2014; Wolf et al., 2016]. Overall these patterns of extreme drought have been mirrored throughout nearly all major terrestrial vegetated biomes of the world, as well as in the key food production regions of every inhabited continent [Ciais et al., 2005; Soja et al., 2007; Cook et al., 2010; Schwalm et al., 2012; Fisher et al., 2013b; van Dijk et al., 2013; Famiglietti, 2014].

© 2017. The Authors.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.



**Figure 1.** Terrestrial evapotranspiration (ET) consumes two-thirds of total global terrestrial precipitation [Oki and Kanae, 2006], and the trajectory of ET is highly uncertain [Mao et al., 2015]. Background image from [hdwallpapers.cat](http://hdwallpapers.cat).

While many ecosystems may be unable to adapt to such changes in drought frequency, duration, or severity, human society has the potential to adapt given the right information at the right time. As it currently stands, however, our collective infrastructure is insufficiently equipped to buffer these changes in water availability, with storage and supply now increasingly outpaced by demand [Vörösmarty et al., 2000; Famiglietti, 2015]. Moreover, drought predictive capabilities are in need of significant improvements. For example, United States drought monitors failed to predict the 2012 U.S. Midwest megadrought in terms of its magnitude and intensity [Freedman, 2012]. This was in large part due to missing information on land-atmosphere coupling, i.e., evapotranspiration (ET), and an underemphasis on the response of vegetation to drought [Meng et al., 2014]. One of the few drought metrics to capture the magnitude, intensity, and timing (i.e., early-warning indicator) of the drought at resolutions applicable for management was based on ET: the Evaporative Stress Index (ESI) [Anderson et al., 2010; Otkin et al., 2016]. Accurate and timely drought forecasting can be a vital tool to water managers who need to know how to allocate dwindling water resources in water-limited regions to benefit society and optimize productivity, while mitigating economic, societal, legal, and ecological damage. Such resource allocation problems are expected to become even more pressing, with projections that a global population of 9B people by 2050 will necessitate a 60% increase in food production, with a commensurate increase in water supplied from already stressed hydrologic systems [IPCC, 2014].

To date, most hydrologic studies have tended to focus on the supply side of the water problem (e.g., precipitation, snow, soil moisture, groundwater), but have largely ignored the demand side (i.e., ET; the loss of water to the atmosphere). However, increasing water demands (both climate-driven and management-driven) and droughts have now made it critical to understand both sides of the supply-demand equation,

		P A N E L S				
		I	II	III	IV	V
<i>ET relevance</i>		Weather: Minutes to Sub-seasonal	Climate Variability & Change	Marine & Terrestrial Ecosystems	Global Hydrological Cycle & Water Resources	Earth Surface & Interior
WORKING GROUPS	A	Extreme Events	Latent heat flux	Ecosystem resilience	Drought-induced mortality	Flash droughts
	B	Water Cycle	Cloud formation, turbulence	Latent heat flux, surface wetting/drying	Plant functioning	Land-atmosphere water flux
	C	Carbon Cycle	Surface roughness	Ecosystem resilience	Transpiration-photosynthesis tradeoff	Ecosystem regulation of water cycle
	D	Technology & Innovations Cross-Cut	Thermal infrared, VSWIR	Thermal infrared, VSWIR	Thermal infrared, VSWIR	Thermal infrared, VSWIR
	E	Applications' Science Cross-Cut	Improving weather predictions	Ecosystem management	Agriculture, rangeland management	Water resources management

**Figure 2.** Evapotranspiration (ET)-based science cross-cuts across all the five U.S. National Research Council Decadal Survey panels and all five of the working groups. The specific science and application targets enabled by ET measurements are highlighted in red within each panel and working group: (IA) The latent heat flux, functionally equivalent to ET, is a driver of fine-scale weather and is impacted by extreme events, particularly heat waves and droughts; (IB) ET provides the primary terrestrial water input for cloud formation as well as turbulence; (IC) ET defines, in part, the type of vegetation that can grow in any given area, and the type of vegetation defines the surface roughness, which affects wind; (ID) Thermal infrared and VSWIR technology and innovations, in particular, will help provide the data to inform understanding of weather; (IE) ET influences weather and subsequent weather predictions; (IIA) Ecosystem water use requirements determine the resilience to extreme events such as droughts, which also impact their ability to feedback to climate through water release and carbon uptake; (IIB) ET is a key component to net surface wetting or drying, and is also the latent heat flux that contributes to the total surface energy balance; (IIC) Like IIA for longer-term mean conditions; (IID) Like ID for reducing uncertainty in climate variability and change; (IIE) Ecosystems can be managed based on water requirements, which can impact climate; (IIIA) Ecosystem water use and requirements are critical for understanding vulnerability to droughts; (IIIB) Plant functioning controls water use; (IIIC) Water loss through transpiration means carbon uptake for photosynthesis, and vice versa; (IIID) Like ID to characterize terrestrial ecosystems; (IIIE) ET is a top priority for agriculture and rangeland management, as well as other applications (e.g., fire); (IVA) ET is the leading predictor of flash droughts; (IVB) ET is the main water cycle pathway that returns water to the atmosphere; (IVC) Equivalent to IIC; (IVD) Like ID for capturing a key water cycle component and a critical variable in quantifying water resources; (IVE) ET, as the major water loss pathway, is a key variable for water resources management; (VB) Volcanic CO<sub>2</sub> degassing would lead to stomatal closure; (VC) Reduction in ET from stomatal closure would be available to soil processes; (VD) Like ID for volcanic CO<sub>2</sub> degassing on ecosystems; and (VE) Insight into volcanic activity.

particularly the loss of water through ET (especially agricultural consumptive use—the predominant managed use of water) when mitigating vegetation stress responses (Figure 1). ET is a keystone climate variable that uniquely links the water cycle (evaporation), energy cycle (latent heat flux), and carbon cycle (transpiration-photosynthesis trade-off) [Monteith, 1965; Wong et al., 1979; Fisher, 2013]. It is the leading climatic predictor of biodiversity [Fisher et al., 2011], the predominant variable needed for water management in agricultural food production (irrigation so that applied water approximates atmospheric demand for ET) [Allen et al., 1998; Anderson et al., 2011], and the leading indicator of extreme event flash droughts [Anderson et al., 2013; Otkin et al., 2016]. ET also plays a critical role in driving weather patterns at the local scale, affecting turbulence, cloud formation, and convection [Miralles et al., 2014; Vergopolan and Fisher, 2016]. In addition, changes in ET can be used to diagnose climate variability and change, e.g., whether the land surface wets or dries over decadal scales [Dai et al., 2004; Sheffield et al., 2012; Greve et al., 2014; Prudhomme et al., 2014; Mao et al., 2015].



Given its importance, ET has provided a key focus for major national and international organizations including, for example, the World Climate Research Programme (WCRP), the United Nations Food and Agriculture Organization (FAO), the US Global Change Research Program (USGCRP), and the US National Research Council (NRC). The current US NRC Decadal Survey 2017, in particular, is evaluating science needs across the spectrum of Earth Sciences to guide policy recommendations for the next decade of space missions; ET-based science and applications are much in consideration. The research and applied sciences communities—represented, in part, as coauthors here—contributed feedback to NRC requests for information, illustrating how ET-based science and applications cross-cut all five Decadal Survey panels and all five of their working groups, and highlighting the importance of this key variable (Figure 2); this Commentary was motivated by those responses. The science communities that can capitalize on improved information on ET are broad and include: (i) Agronomy; (ii) Ecology; (iii) Hydrology; (iv) Atmospheric Science; (v) Climate; (vi) Carbon Cycle; (vii) Coastal Science; (viii) Computer/Data Science; (ix) Statistics; and, (x) Policy/Economics.

ET-based science, from leaf to global scales, has advanced significantly over the past few decades [e.g., Baldocchi, 2005; Gedney *et al.*, 2006; Jung *et al.*, 2009; Anderson *et al.*, 2011; Vinukollu *et al.*, 2011; Mueller *et al.*, 2013; Polhamus *et al.*, 2013; Dolman *et al.*, 2014; Badgley *et al.*, 2015; McCabe *et al.*, 2016; Miralles *et al.*, 2016; Zhang *et al.*, 2016]. We are now able to map ET remotely at multiple scales with relatively high accuracy, and can leverage an extended network of eddy covariance FLUXNET towers throughout the world for in situ assessment [Baldocchi *et al.*, 2001]. Information on ET is used in a wide variety of scientific explorations and societal applications, including, but not limited to, biodiversity assessments [Gaston, 2000; Fisher *et al.*, 2011], regional water balance closures [Sahoo *et al.*, 2011; Marshall *et al.*, 2012; Armanios and Fisher, 2014; Chen *et al.*, 2014], climate and cloud formation [Shukla and Mintz, 1982; Rabin *et al.*, 1990; Mölders and Raabe, 1996], agricultural management [Allen *et al.*, 1998; Farahani *et al.*, 2007; Allen *et al.*, 2011], water resources management [Bastiaanssen *et al.*, 2005; Anderson *et al.*, 2012], detection of drought and heat waves [Rind *et al.*, 1990; Vicente-Serrano *et al.*, 2010; Miralles *et al.*, 2014; Otkin *et al.*, 2014], urban heat islands [Oke, 1982; Taha, 1997], and water rights litigation [Allen *et al.*, 2005; Anderson *et al.*, 2012].

Despite the sustained and significant advances that have been made, there remain a multitude of critical Earth System Science questions and challenges that require further insight into ET before they will be fully resolved. These largely capitalize on refinements and continuity within our recent advances in ET-based science fostered by increased spatial and temporal resolution, as well as accuracy. As a product of the NRC Decadal Survey process, we identified and synthesized the principal outstanding knowledge gaps into ten research and applied science questions:

1. How are natural and managed ecosystems responding to changes in climate and water availability?
2. How much water do different plant assemblages in ecosystems use and how much do they need?
3. What is the timing of water use among ecosystems, and how does that vary diurnally, seasonally, and annually?
4. How do changes in plant water availability, access, use, and stress regulate photosynthesis and productivity?
5. How is ET partitioned into transpiration, soil evaporation, and interception evaporation, and how are these components differentially impacted by a changing temperature, CO<sub>2</sub>, and hydrologic regime?
6. How does ET redistribute water in a strengthening or weakening global hydrological cycle, and what are the underlying causes and consequences?
7. How do changes in ET amplify or dampen climate feedbacks, land-atmosphere coupling, and hydrometeorological extremes at local to regional scales?
8. Can ET observations help constrain and improve short-term weather prediction and future climate projections at seasonal to interannual timescales?
9. Can we unify the water, carbon, and energy cycles globally from space-borne observations, with ET as the linking variable?
10. How can information on ET be applied to optimize sustainable water allocations, agricultural water use, food production, ecosystem management, and hence water and food security in a changing climate to meet the demands of a growing population?

As soon as possible, we need to advance and implement strategies for the collection of critical information gathering on ET to ensure food and water security, and to provide data that will enhance the ability of

climate and biospheric models to simulate feedbacks associated with hydrologic and ecosystem responses to a changing climate.

## 2. Path Forward

To address these science and applications questions, we must be able to map ET with very high fidelity:

1. *High accuracy*: Increased accuracy will allow improved differentiation of water use and water stress among different crops, species, and ecosystems, as well as to enable more efficient water management (Goal: less than 10% relative error);
2. *High spatial resolution*: The length scales required to detect spatially heterogeneous responses to water environments must consider the “field-scale” of agricultural plots, narrow riparian zones, and mixed-species forest/ecosystem assemblages (Goal: 10–100 m);
3. *High temporal resolution*: ET is highly variable both within and among days. Vegetation may regulate transpiration by closing leaf stomata, impacting water management, biomass production, and atmospheric feedbacks. Water management applications of ET require accurate ET information that is provided at timeframes associated with daily irrigation decisions and scheduling, as well as a capacity to detect vegetation responses to water stress in near real-time (Goal: daily to subdaily);
4. *Large spatial coverage*: Global coverage enables detection of large-scale droughts, is necessary to understand climate feedbacks, is required to close the global water and energy budgets, and ensures consistency and dependability in measurements across regions and shared resources (Goal: global terrestrial surface); and
5. *Long-term monitoring*: Because heatwaves, droughts and drought responses evolve over the course of multiple years, and as climate becomes increasingly variable, the need for long-term observations will likewise be increasingly critical (Goal: decadal-scale mission and data science continuity).

ET is a multifaceted variable, supplied by precipitation and subsequent root zone and surface soil moisture, and controlled by a combination of radiative, atmospheric, and vegetation drivers obtainable from remote sensing [Su, 2002; Allen *et al.*, 2007; Fisher *et al.*, 2008; Anderson *et al.*, 2011; Miralles *et al.*, 2011; Mu *et al.*, 2011]. Because ET cannot be measured directly from space at high resolutions as a water variable, it must be physically derived as an energy variable (i.e., the latent heat flux, or the amount of energy used in evaporating water) with multiple types of measurements necessary to ensure that the abiotic and biotic controls are adequately captured. Solar radiation, humidity, air temperature, wind speed, and soil moisture regulate the transfer of water from the land into the air. Information on phenology and vegetation cover is necessary for seasonal dynamics and relative magnitudes of ET fluxes. The evaporative flux in turn modifies the land surface temperature.

In addition to space-based observations, important ground-based observations synergistically complement these data, particularly for water management applications: agricultural practices (irrigation type/management, planting decisions, nutrients, soil composition, tilling practices, seed types), water quality, and plant plasticity/sensitivity/adaptation response—all of which are coupled with computational models (crop, climate, water). Physically based models are critical integrators of these measurements and information, and must continue to be scrutinized, tested, and refined [Vinukollu *et al.*, 2011; Polhamus *et al.*, 2013; Chen *et al.*, 2014; Ershadi *et al.*, 2014; Prudhomme *et al.*, 2014; McCabe *et al.*, 2016; Michel *et al.*, 2016; Miralles *et al.*, 2016]. In situ measurements of ET from eddy covariance, Bowen ratio systems, flux-gradient approaches, and lysimeters, as well as water balance approaches, are useful tools for such analyses [Howell *et al.*, 1991; Baldocchi *et al.*, 2001; Fisher *et al.*, 2011].

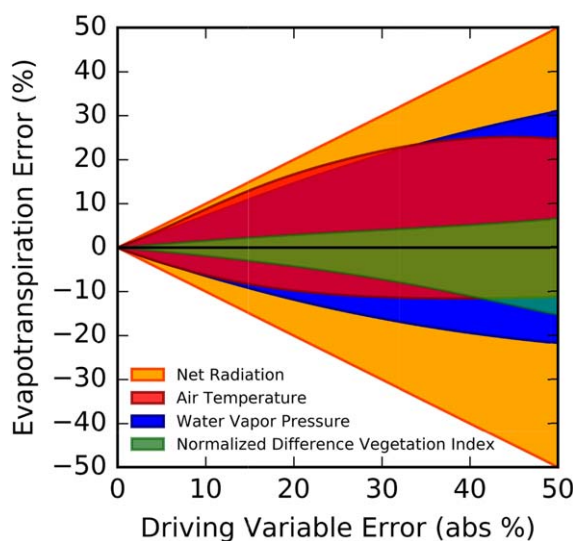
At the local scale, thermal infrared (TIR) observations of land surface temperature are used to capture fine spatial and temporal dynamics associated with heterogeneous land surface processes controlling energy partitioning and ET [Bastiaanssen *et al.*, 1998; Allen *et al.*, 2007; Ershadi *et al.*, 2013]. TIR measurements across multiple bands (>4) ensure that land surface temperature and emissivity are retrieved to within 1 K accuracy (assuming a precision of 0.3 K); this allows ET estimates to be within 10% relative error from land surface temperature uncertainty [Hook *et al.*, 2004; Blonquist *et al.*, 2009; Cammalleri *et al.*, 2012; Hulley *et al.*, 2012; Fisher *et al.*, 2013a]. Measurements should be acquired at high spatial resolutions (10–100 m) and high temporal resolutions (daily, diurnal), as warranted above [Allen *et al.*, 2007; Chen *et al.*, 2008; Allen *et al.*, 2011; Anderson *et al.*, 2012; Kilic *et al.*, 2016].

At large spatial and temporal scales, net radiation is among the most important drivers of ET, explaining up to 80% of variability in ET, and must be obtained from a combination of radiative, atmospheric, and surface observations (e.g., VSWIR, TIR) [Fisher et al., 2008; Fisher et al., 2009; Jiménez et al., 2011; Polhamus et al., 2013; Badgley et al., 2015; Verma et al., 2016]. Global-scale ET models are highly reliant on accurate net radiation [Fisher et al., 2008; Miralles et al., 2011]. As such, errors in net radiation can have proportionally large impacts on errors in ET, and should be obtained to within less than 10% relative error to ensure the goal of less than 10% relative error in ET.

High-quality meteorology, i.e., near surface air temperature and water vapor pressure, is needed for accurate flux retrievals by differentiating microclimates. In general, meteorological variables are well-mixed relative to the much more heterogeneous land surface variables, so meteorological spatial resolution requirements may be less stringent (<5 km), although temporal resolution requirements remain high (daily, diurnal) [Anderson et al., 1997; Allen et al., 2007; Fisher et al., 2008; Allen et al., 2011]. Meteorological drivers should be obtained with less than 15% relative error, though there is spatiotemporal dependence on ET error, e.g., when weather patterns are rapidly changing, and in arid/semiarid regions.

Finally, commensurate and collocated visible and near infrared (VNIR) measurements for phenology and vegetation cover are also required at high spatial and temporal resolutions (10–100 m, daily–weekly) [Anderson et al., 1997; Allen et al., 2007; Fisher et al., 2008; Allen et al., 2011]. At the global scale, these should be obtained with less than 25% relative error, but are particularly important during phenological events, e.g., spring leaf-out timing, and have considerably more weight at the local scale, during crop planting and harvest, and in arid/semiarid regions [Polhamus et al., 2013].

In short, ET requires a combination of accurate information from TIR (especially for local scales), net radiation (especially for large scales), meteorology, and VNIR (for vegetation characteristics). We show, for example, the ET error sensitivity to driving variable error at the global annual average scale for one global-scale ET model (PT-JPL: Fisher et al. [2008]) (Figure 3); these sensitivities would vary depending on the model, as well as in space and time. Additionally, soil moisture information can help improve ET estimation, although is not required [Entekhabi et al., 2010; Miralles et al., 2011; Purdy et al., 2016]. Incorporating complementary carbon cycle observations of vegetation response, such as chlorophyll [Houborg et al., 2015], carotenoids, and fluorescence [Frankenberg et al., 2011] can also aid in better discriminating coupled water and carbon responses.



**Figure 3.** At the global annual-averaged scale, error in evapotranspiration for the PT-JPL model [Fisher et al., 2008] is highly sensitive to error in radiative (net radiation) and meteorological (water vapor pressure, air temperature) drivers, and somewhat sensitive to vegetation cover and phenology drivers (normalized difference vegetation index). This sensitivity varies widely in space and time, as well as with model.

A few current and planned space missions/instruments capture some, but not all, of the components necessary to meet the requirements for addressing the key science questions, challenges, and societal benefits described above. For example, Landsat provides excellent spatial resolution (>60 m), but poor temporal resolution (16 days) for TIR and VSWIR. MODIS/VIIRS provide good revisit time (daily), and good spatial resolution for meteorological and net radiation components, but insufficient spatial resolution for TIR and VSWIR ( $\geq 375$  m). GOES and other geostationary weather satellites capture the diurnal cycle, but at the expense of spatial resolution (>3 km) and cohesive global coverage. ESA's Sentinel-2 provides good spatial (10–60 m) and temporal (5 days) resolutions for VSWIR, but is lacking TIR. ECOSTRESS will provide good spatial (70 m) and spectral resolutions for TIR (5 bands), and good temporal resolution (3–5 days, variable diurnal sampling), but is not an extended mission (1 year) and does not capture the high latitudes. Moreover, TIR

retrievals in general are limited to clear-sky conditions, but additional all-sky retrievals can be made from microwave Ka-band sensors, albeit at lower spatial resolution [Holmes *et al.*, 2015]. The proposed HypsIRI mission (identified as a Tier 2 mission in the 2007 Decadal Survey) could provide excellent TIR and VSWIR spatial resolution ( $\leq 60$  m), good temporal resolution (5 days), and global land coverage, but is only in Pre-Phase A (i.e., not yet approved) [Lee *et al.*, 2015]. At present, the instrumentation and data algorithms for ET are mature; consequently, an orbital mission or set of missions to support ET capability from space draws upon extensive heritage and demonstrated need. It is only the flight coverage with requisite concurrent measurements that needs to be improved and optimized for ET observation, science, and applications. The timing is urgent to achieve these objectives as soon as possible.

### 3. Conclusions

ET science and applications have significantly advanced across a wide array of fields over the past few decades; yet, critical outstanding ET-based science and application questions remain from local to global scales due to deficiencies in our observational capabilities. No existing or planned space mission has been specified to fully meet the spatial, temporal, spectral, and accuracy requirements outlined for complete ET-based science and applications. The coauthors, on behalf of the larger science and applications communities that use ET data, strongly support national and international programs and policies, such as the US NRC Decadal Survey, to in prioritization of ET-based investments and programs to advance the critical and urgent science and application questions described within this commentary.

#### Acknowledgments

Three reviewers and the *WRR* Associate Editor provided useful suggestions that improved the manuscript. JBF was supported in part by NASA THP, SUSMAP, INCA, ECOSTRESS, and JPL internal investment. M.F.M. acknowledges support from the King Abdullah University of Science and Technology. D.G.M. acknowledges support from the European Research Council (ERC) under grant agreement 715254 (DRY2DRY). This work was led out of the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, California Institute of Technology. Government sponsorship acknowledged. Copyright 2016. All rights reserved.

#### References

- AghaKouchak, A., L. Cheng, O. Mazdiyasni, and A. Farahmand (2014), Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought, *Geophys. Res. Lett.*, *41*, 8847–8852, doi:10.1002/2014GL062308.
- Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998), Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements (*FAO Irrigation and Drainage Paper*), 328 pp., FAO—Food and Agric. Organ. of the U. N., Rome.
- Allen, R. G., M. Tasumi, and R. Trezza (2007), Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-model, *J. Irrig. Drain. Eng.*, *133*, 380–394.
- Allen, R. G., M. Tasumi, A. Morse, and R. Trezza (2005), A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning, *Irrig. Drain. Syst.*, *19*(3–4), 251–268.
- Allen, R. G., L. S. Pereira, T. A. Howell, and M. E. Jensen (2011), Evapotranspiration information reporting: I. Factors governing measurement accuracy, *Agric. Water Manage.*, *98*(6), 899–920.
- Anderson, M. C., J. M. Norman, G. R. Diak, W. P. Kustas, and J. R. Mecikalski (1997), A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing, *Remote Sens. Environ.*, *60*(2), 195–216.
- Anderson, M. C., C. Hain, B. Wardlow, A. Pimstein, J. R. Mecikalski, and W. P. Kustas (2010), Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental United States, *J. Clim.*, *24*(8), 2025–2044.
- Anderson, M. C., et al. (2011), Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery, *Hydrol. Earth Syst. Sci.*, *15*, 223–239.
- Anderson, M. C., R. G. Allen, A. Morse, and W. P. Kustas (2012), Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources, *Remote Sens. Environ.*, *122*(0), 50–65.
- Anderson, M. C., C. Hain, J. Otkin, X. Zhan, K. Mo, M. Svoboda, B. Wardlow, and A. Pimstein (2013), An intercomparison of drought indicators based on thermal remote sensing and NLDAS-2 simulations with US Drought Monitor classifications, *J. Hydrometeorol.*, *14*(4), 1035–1056.
- Armanios, D. E., and J. B. Fisher (2014), Measuring water availability with limited ground data: Assessing the feasibility of an entirely remote-sensing-based hydrologic budget of the Rufiji Basin, Tanzania, using TRMM, GRACE, MODIS, SRB, and AIRS, *Hydrol. Processes*, *28*(3), 853–867.
- Badgley, G., J. B. Fisher, C. Jiménez, K. P. Tu, and R. K. Vinukollu (2015), On uncertainty in global evapotranspiration estimates from choice of input forcing datasets, *J. Hydrometeorol.*, *16*(4), 1449–1455.
- Baldocchi, D., et al. (2001), FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bull. Am. Meteorol. Soc.*, *82*(11), 2415–2434.
- Baldocchi, D. D. (2005), The role of biodiversity on the evaporation of forests, in *Forest Diversity and Function: Temperate and Boreal Systems*, edited by M. Scherer-Lorenzen, C. Körner and E.-D. Schulze, pp. 131–148, Springer, Berlin.
- Bastiaanssen, W. G. M., M. Menenti, R. A. Feddes, and A. A. M. Holtslag (1998), A remote sensing energy balance algorithm for land, SEBAL: 1. Formulation, *J. Hydrol.*, *212–213*, 198–212.
- Bastiaanssen, W. G. M., E. Noordman, H. Pelgrum, G. Davids, B. Thoreson, and R. Allen (2005), SEBAL model with remotely sensed data to improve water-resources management under actual field conditions, *J. Irrig. Drain. Eng.*, *131*(1), 85–93.
- Blonquist Jr, J. M., J. M. Norman, and B. Bugbee (2009), Automated measurement of canopy stomatal conductance based on infrared temperature, *Agric. For. Meteorol.*, *149*(11), 1931–1945.
- Camalleri, C., M. C. Anderson, G. Ciraolo, G. D'Urso, W. P. Kustas, G. La Loggia, and M. Minacapilli (2012), Applications of a remote sensing-based two-source energy balance algorithm for mapping surface fluxes without in situ air temperature observations, *Remote Sens. Environ.*, *124*(0), 502–515.
- Chen, X., Y. Rubin, S. Ma, and D. Baldocchi (2008), Observations and stochastic modeling of soil moisture control on evapotranspiration in a Californian oak savanna, *Water Resour. Res.*, *44*, W08409, doi:10.1029/2007WR006646.



- Chen, Y., J. Xia, S. Liang, J. Feng, J. B. Fisher, X. Li, X. Li, S. Liu, Z. Ma, and A. Miyata (2014), Comparison of satellite-based evapotranspiration models over terrestrial ecosystems in China, *Remote Sens. Environ.*, **140**, 279–293.
- Ciais, P., et al. (2005), Europe-wide reduction in primary productivity caused by the heat and drought in 2003, *Nature*, **437**(7058), 529–533.
- Cook, E. R., K. J. Anchukaitis, B. M. Buckley, R. D. D'Arrigo, G. C. Jacoby, and W. E. Wright (2010), Asian monsoon failure and megadrought during the last millennium, *Science*, **328**(5977), 486–489.
- Dai, A., K. E. Trenberth, and T. Qian (2004), A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, **5**, 1117–1130.
- Dolman, A. J., D. G. Miralles, and R. A. Jeu (2014), Fifty years since Monteith's 1965 seminal paper: The emergence of global ecohydrology, *Ecohydrology*, **7**(3), 897–902.
- Entekhabi, D., et al. (2010), The Soil Moisture Active Passive (SMAP) mission, *Proc. IEEE*, **98**(5), 704–716.
- Ershadi, A., M. F. McCabe, J. P. Evans, G. Mariethoz, and D. Kavetski (2013), A Bayesian analysis of sensible heat flux estimation: Quantifying uncertainty in meteorological forcing to improve model prediction, *Water Resour. Res.*, **49**, 2343–2358, doi:10.1002/wrcr.20231.
- Ershadi, A., M. F. McCabe, J. P. Evans, N. W. Chaney, and E. F. Wood (2014), Multi-site evaluation of terrestrial evaporation models using FLUXNET data, *Agric. For. Meteorol.*, **187**, 46–61.
- Famiglietti, J. (2015), California Has About One Year of Water Stored. Will You Ration Now?, *Los Angeles Times*, **12**.
- Famiglietti, J. S. (2014), The global groundwater crisis, *Nat. Clim. Change*, **4**(11), 945–948.
- Farahani, H. J., T. A. Howell, W. J. Shuttleworth, and W. C. Bausch (2007), Evapotranspiration: Progress in measurement and modeling in agriculture, *Trans. ASABE*, **50**(5), 1627–1638.
- Fisher, J. B. (2013), Land-atmosphere interactions: Evapotranspiration, in *Encyclopedia of Remote Sensing*, edited by E. Njoku, pp. 1–5, Springer, Berlin.
- Fisher, J. B., K. Tu, and D. D. Baldocchi (2008), Global estimates of the land-atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites, *Remote Sens. Environ.*, **112**(3), 901–919.
- Fisher, J. B., et al. (2009), The land-atmosphere water flux in the tropics, *Global Change Biol.*, **15**, 2694–2714.
- Fisher, J. B., R. H. Whittaker, and Y. Malhi (2011), ET Come Home: A critical evaluation of the use of evapotranspiration in geographical ecology, *Global Ecol. Biogeogr.*, **20**, 1–18.
- Fisher, J. B., K. Mallick, J.-H. Lee, G. C. Hulley, C. G. Hughes, and S. J. Hook (2013a), Uncertainty in evapotranspiration from uncertainty in land surface temperature, in *American Meteorological Society*, Austin, Tex.
- Fisher, J. B., et al. (2013b), African tropical rainforest net carbon dioxide fluxes in the twentieth century, *Philos. Trans. R. Soc. B*, **368**(1625), 1–9.
- Frankenberg, C., J. B. Fisher, J. Worden, G. Badgley, S. S. Saatchi, J.-E. Lee, G. C. Toon, A. Butz, A. Kuze, and T. Yokota (2011), New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity, *Geophys. Res. Lett.*, **38**, L17706, doi:10.1029/2011GL048738.
- Freedman, A. (2012), *Lack of Warning on Drought Reflects Forecasting Flaws*, Clim. Central. [Available at <http://www.climatecentral.org/news/lack-of-warning-on-2012-us-drought-reflects-flaws-in-forecasting-14823/>]
- Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti (2014), Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks, *J. Clim.*, **27**(2), 511–526.
- Gaston, K. J. (2000), Global patterns in biodiversity, *Nature*, **405**(6783), 220–227.
- Gedney, N., P. M. Cox, R. A. Betts, O. Boucher, C. Huntingford, and P. A. Stott (2006), Detection of a direct carbon dioxide effect in continental river runoff records, *Nature*, **439**, 835–838.
- Greve, P., B. Orlowsky, B. Mueller, J. Sheffield, M. Reichstein, and S. I. Seneviratne (2014), Global assessment of trends in wetting and drying over land, *Nat. Geosci.*, **7**(10), 716–721.
- Holmes, T., W. Crow, C. Hain, M. Anderson, and W. Kustas (2015), Diurnal temperature cycle as observed by thermal infrared and microwave radiometers, *Remote Sens. Environ.*, **158**, 110–125.
- Hook, S. J., G. Chandler, J. A. Barsi, R. E. Alley, A. Abtahi, F. D. Palluconi, B. L. Markham, R. C. Richards, S. G. Schladow, and D. L. Helder (2004), In-flight validation and recovery of water surface temperature with Landsat-5 thermal infrared data using an automated high-altitude lake validation site at Lake Tahoe, *IEEE Trans. Geosci. Remote Sens.*, **42**(12), 2767–2776.
- Houborg, R., M. F. McCabe, A. Cescatti, and A. A. Gitelson (2015), Leaf chlorophyll constraint on model simulated gross primary productivity in agricultural systems, *Int. J. Appl. Earth Observ. Geoinform.*, **43**, 160–176.
- Howell, T. A., A. D. Schneider, and M. E. Jensen (1991), History of lysimeter design and use for evapotranspiration measurements, paper presented at Proceedings of the International Symposium on Lysimetry, ASCE, Honolulu, Hawaii.
- Hulley, G. C., C. G. Hughes, and S. J. Hook (2012), Quantifying uncertainties in land surface temperature and emissivity retrievals from ASTER and MODIS thermal infrared data, *J. Geophys. Res.*, **117**, D23113, doi:10.1029/2012JD018506.
- IPCC (2014), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1132 pp., Cambridge Univ. Press, Cambridge, U. K.
- Jiménez, C., et al. (2011), Global inter-comparison of 12 land surface heat flux estimates, *J. Geophys. Res.*, **116**, D02102, doi:10.1029/2010JD014545.
- Jiménez-Muñoz, J. C., C. Mattar, J. Barichivich, A. Santamaría-Artigas, K. Takahashi, Y. Malhi, J. A. Sobrino, and G. van der Schrier (2016), Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016, *Sci. Rep.*, **6**, 1–12.
- Jung, M., M. Reichstein, and A. Bondeau (2009), Towards global empirical upscaling of FLUXNET eddy covariance observations: Validation of a model tree ensemble approach using a biosphere model, *Biogeosciences*, **6**, 2001–2013.
- Kilic, A., R. Allen, R. Trezza, I. Ratcliffe, B. Kamble, C. Robison, and D. Ozturk (2016), Sensitivity of evapotranspiration retrievals from the METRIC processing algorithm to improved radiometric resolution of Landsat 8 thermal data and to calibration bias in Landsat 7 and 8 surface temperature, *Remote Sens. Environ.*, **185**, 198–209.
- Lee, C. M., M. L. Cable, S. J. Hook, R. O. Green, S. L. Ustin, D. J. Mandl, and E. M. Middleton (2015), An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities, *Remote Sens. Environ.*, **167**, 6–19.
- Lewis, S. L., P. M. Brando, O. L. Phillips, G. M. F. van der Heijden, and D. Nepstad (2011), The 2010 Amazon drought, *Science*, **331**(6017), 554.
- Long, D., B. R. Scanlon, L. Longuevergne, A. Y. Sun, D. N. Fernando, and H. Save (2013), GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas, *Geophys. Res. Lett.*, **40**, 3395–3401, doi:10.1002/grl.50655.
- Mallya, G., L. Zhao, X. Song, D. Niyogi, and R. Govindaraju (2013), 2012 midwest drought in the United States, *J. Hydrol. Eng.*, **18**(7), 737–745.
- Mao, J., W. Fu, X. Shi, D. M. Ricciuto, J. B. Fisher, R. E. Dickinson, Y. Wei, W. Shem, S. Piao, and K. Wang (2015), Disentangling climatic and anthropogenic controls on global terrestrial evapotranspiration trends, *Environ. Res. Lett.*, **10**(9), 094008.



- Marshall, M., C. Funk, and J. Michaelsen (2012), Examining evapotranspiration trends in Africa, *Clim. Dyn.*, 38(9–10), 1849–1865.
- McCabe, M. F., A. Ershadi, C. Jimenez, D. G. Miralles, D. Michel, and E. F. Wood (2016), The GEWEX LandFlux project: Evaluation of model evaporation using tower-based and globally gridded forcing data, *Geosci. Model Dev.*, 9(1), 283–305.
- Meng, X., J. Evans, and M. McCabe (2014), The impact of observed vegetation changes on land–atmosphere feedbacks during drought, *J. Hydrometeorol.*, 15(2), 759–776.
- Michel, D., C. Jiménez, D. Miralles, M. Jung, M. Hirschi, A. Ershadi, B. Martens, M. McCabe, J. Fisher, and Q. Mu (2016), The WACMOS-ET project—Part 1: Tower-scale evaluation of four remote-sensing-based evapotranspiration algorithms, *Hydrol. Earth Syst. Sci.*, 20(2), 803–822.
- Miralles, D. G., T. R. H. Holmes, R. A. M. De Jeu, J. H. Gash, A. G. C. A. Meesters, and A. J. Dolman (2011), Global land-surface evaporation estimated from satellite-based observations, *Hydrol. Earth Syst. Sci.*, 15(2), 453–469.
- Miralles, D. G., A. J. Teuling, C. C. van Heerwaarden, and J. Vila-Guerau de Arellano (2014), Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation, *Nat. Geosci.*, 7(5), 345–349.
- Miralles, D. G., C. Jiménez, M. Jung, D. Michel, A. Ershadi, M. McCabe, M. Hirschi, B. Martens, A. Dolman, and J. Fisher (2016), The WACMOS-ET project, part 2: Evaluation of global terrestrial evaporation data sets, *Hydrol. Earth Syst. Sci.*, 20(2), 823–842.
- Mölders, N., and A. Raabe (1996), Numerical investigations on the influence of subgrid-scale surface heterogeneity on evapotranspiration and cloud processes, *J. Appl. Meteorol.*, 35(6), 782–795.
- Monteith, J. L. (1965), Evaporation and the environment, *Symp. Soc. Explor. Biol.*, 19, 205–234.
- Mu, Q., M. Zhao, and S. W. Running (2011), Improvements to a MODIS global terrestrial evapotranspiration algorithm, *Remote Sens. Environ.*, 111, 519–536.
- Mueller, B., M. Hirschi, C. Jimenez, P. Ciais, P. Dirmeyer, A. Dolman, J. Fisher, M. Jung, F. Ludwig, and F. Maignan (2013), Benchmark products for land evapotranspiration: LandFlux-EVAL multi-dataset synthesis, *Hydrol. Earth Syst. Sci.*, 17, 3707–3720.
- Oke, T. R. (1982), The energetic basis of the urban heat island, *Quart. J. R. Meteorol. Soc.*, 108(455), 1–24.
- Oki, T., and S. Kanae (2006), Global hydrological cycles and world water resources, *Science*, 313(5790), 1068–1072.
- Otkin, J. A., M. C. Anderson, C. Hain, and M. Svoboda (2014), Examining the relationship between drought development and rapid changes in the evaporative stress index, *J. Hydrometeorol.*, 15(3), 938–956.
- Otkin, J. A., M. C. Anderson, C. Hain, M. Svoboda, D. Johnson, R. Mueller, T. Tadesse, B. Wardlaw, and J. Brown (2016), Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought, *Agric. For. Meteorol.*, 218, 230–242.
- Phillips, O. L., et al. (2009), Drought sensitivity of the Amazon rainforest, *Science*, 323(5919), 1344–1347.
- Polhamus, A., J. B. Fisher, and K. P. Tu (2013), What controls the error structure in evapotranspiration models?, *Agric. For. Meteorol.*, 169(0), 12–24.
- Prudhomme, C., I. Giuntoli, E. L. Robinson, D. B. Clark, N. W. Arnell, R. Dankers, B. M. Fekete, W. Franssen, D. Gerten, and S. N. Gosling (2014), Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, *Proc. Natl. Acad. Sci. U. S. A.*, 111(9), 3262–3267.
- Purdy, A. J., J. B. Fisher, M. Goulden, and J. S. Famiglietti (2016), Potential for SMAP soil moisture observations to improve remote sensing of evapotranspiration algorithms, paper presented at 2016 Fall Meeting, AGU, San Francisco, Calif.
- Rabin, R. M., D. J. Stensrud, S. Stadler, P. J. Wetzel, and M. Gregory (1990), Observed effects of landscape variability on convective clouds, *Bull. Am. Meteorol. Soc.*, 71(3), 272–280.
- Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy (1990), Potential evapotranspiration and the likelihood of future drought, *J. Geophys. Res.*, 95(D7), 9983–10,004.
- Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L. E. Aragão, L. O. Anderson, R. B. Myneni, and R. Nemani (2013), Persistent effects of a severe drought on Amazonian forest canopy, *Proc. Natl. Acad. Sci. U. S. A.*, 110(2), 565–570.
- Sahoo, A. K., M. Pan, T. J. Troy, R. K. Vinukollu, J. Sheffield, and E. F. Wood (2011), Reconciling the global terrestrial water budget using satellite remote sensing, *Remote Sens. Environ.*, 115(8), 1850–1865.
- Schwalm, C. R., C. A. Williams, K. Schaefer, D. Baldocchi, T. A. Black, A. H. Goldstein, B. E. Law, W. C. Oechel, and R. L. Scott (2012), Reduction in carbon uptake during turn of the century drought in western North America, *Nat. Geosci.*, 5(8), 551–556.
- Sheffield, J., E. F. Wood, and M. L. Roderick (2012), Little change in global drought over the past 60 years, *Nature*, 491(7424), 435–438.
- Shukla, J., and Y. Mintz (1982), Influence of land-surface evapotranspiration on the earth's climate, *Science*, 215(4539), 1498–1501.
- Soja, A. J., N. M. Tchebakova, N. H. F. French, M. D. Flannigan, H. H. Shugart, B. J. Stocks, A. I. Sukhinin, E. I. Parfenova, F. S. Chapin II, and P. W. Stackhouse Jr. (2007), Climate-induced boreal forest change: Predictions versus current observations, *Global Planet. Change*, 56(3–4), 274–296.
- Su, Z. (2002), The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes, *Hydrol. Earth Syst. Sci.*, 6, 85–99.
- Syed, T. H., J. S. Famiglietti, D. P. Chambers, J. K. Willis, and K. Hillburn (2010), Satellite-based global-ocean mass balance estimates of inter-annual variability and emerging trends in continental freshwater discharge, *Proc. Natl. Acad. Sci. U. S. A.*, 107(42), 17,916–17,921.
- Taha, H. (1997), Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat, *Energy Build.*, 25(2), 99–103.
- van Dijk, A. I. J. M., H. E. Beck, R. S. Crosbie, R. A. M. de Jeu, Y. Y. Liu, G. M. Podger, B. Timbal, and N. R. Viney (2013), The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society, *Water Resour. Res.*, 49, 1040–1057, doi:10.1002/wrcr.20123.
- Vergopolan, N., and J. B. Fisher (2016), The impact of deforestation on the hydrological cycle in Amazonia as observed from remote sensing, *Int. J. Remote Sens.*, 37(22), 5412–5430.
- Verma, M., et al. (2016), Global daily surface net-radiation at 5 km from MODIS, *Remote Sens.*, 8(739), 1–20.
- Vicente-Serrano, S. M., S. Beguería, and J. I. López-Moreno (2010), A multiscale drought index sensitive to global warming: The standardized precipitation evapotranspiration index, *J. Clim.*, 23(7), 1696–1718.
- Vinukollu, R. K., E. F. Wood, C. R. Ferguson, and J. B. Fisher (2011), Global estimates of evapotranspiration for climate studies using multi-sensor remote sensing data: Evaluation of three process-based approaches, *Remote Sens. Environ.*, 115, 801–823.
- Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global water resources: Vulnerability from climate change and population growth, *Science*, 289, 284–288.
- Wolf, S., et al. (2016), Warm spring reduced carbon cycle impact of the 2012 US summer drought, *Proc. Natl. Acad. Sci. U. S. A.*, 113(21), 5880–5885.
- Wong, S., I. Cowan, and G. Farquhar (1979), Stomatal conductance correlates with photosynthetic capacity, *Nature*, 282, 424–426.
- Zhang, Y., J. L. Peña-Arancibia, T. R. McVicar, F. H. Chiew, J. Vaze, C. Liu, X. Lu, H. Zheng, Y. Wang, and Y. Y. Liu (2016), Multi-decadal trends in global terrestrial evapotranspiration and its components, *Sci. Rep.*, 6(19124), 1–12.
- Ziegler, A. D., J. Sheffield, E. P. Maurer, B. Nijssen, E. F. Wood, and D. P. Lettenmaier (2003), Detection of intensification in global and continental-scale hydrological cycles: Temporal scale of evaluation, *J. Clim.*, 16(3), 535–547.